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Attention: Mr. Douglas M. Pollock

Subject: Contract No. MDA972-93-C-0057; GTEL Project No. 852
Final Technical Report (SLIN 0002AD)

Dear Mr. Pollock:

GTE Laboratories Incorporated hereby submits the subject report which documents the results of its technical effort in performance of the Methods and Components for Optical Contention Resolution in High Speed Networks Project.

If you should have any questions or require any additional information or further clarification, please contact me at (617)466-2954.

Sincerely,

Deidre B. Ryan

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Contracts Manager

19960603 023

Enclosure

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METHODS AND COMPONENTS FOR OPTICAL CONTENTION RESOLUTION IN HIGH SPEED NETWORKS

ARPA Order No. 9339

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Final Report

Submitted by:

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Table of contents

Executive summary

GTE Laboratories Incorporated partnered in the CORD project with University of Massachusetts and Stanford University to develop and demonstrate the feasibility of optical packet switching technology for application in high-speed WDM networks. This technology was developed to resolve data packet contentions in a transparent optical network. The objective of this project was to demonstrate an optical, WDM packet-switched star network operating at 2.5 Gbps with shared network resources. Packet contentions in this high-speed environment are resolved in the optical domain using optical 2x2 switches and fiber delay lines in a contention resolution optical (CRO) configuration. Two complete 2.5 Gbps nodes were built with transmission in 1.3 μm window. Channel spacing of the two WDM channels is about 10 nm. Figure 2 shows the network demonstration and task assignments.

The project responsibilities were divided into optical hardware development by GTE Laboratories, electronic control and signaling by Stanford University, and optimization and performance evaluation by the University of Massachusetts. The GTE Laboratories' responsibility included:

- Design, development and construction of an optical signal processing unit (CRO) for dual wavelength operation,
- Development of a digital optical switch implemented on a III-V semiconductor substrate, and
- Integration and assembly of optical components in the optical processor.

Construction of the CRO module proceeded on two parallel paths. A unit was designed and built using $LiNbO_3$ switches to avoid delays in delivery of this module to the testbed at Stanford University. In parallel, the optical switch was developed with a goal to meet the needs of this contract. The CRO preprototype subsystem was built using commercial components such as amplifiers, switches, and dual wavelength WDM units. Assembly, alignments, special splicing, testing and characterization were done in house. The assembled CRO unit was then shipped to Stanford where control circuitry was added. Fiber alignment modifications were performed at Stanford University to achieve better polarization stability.

The optical switch development effort at GTE Laboratories produced considerable progress in design, prototyping and development of fabrication processes. However, the length of this contract period was insufficient to produce a working, packaged device prototype. Long delays in receiving InP wafers from both EPI and Sumitomo resulted in months of lost time and slowed down considerably the development effort. The results achieved in this work included demonstration of 1x2 switches with excellent extinction ratio and polarization balance, demonstration of a 2x2 switch, and completion of a packageable switch design optimized for low loss and high extinction ratio.

An important conclusion from this effort is that assembly and packaging of opto-electronic components is key to achieving performance and practicality in subsystems. It could be very complex due to the nature of components used, as was the case in the CRO assembly. The CRO module was assembled using discreet, fiber pigtailed components interconnected by splices and connectors. This introduces large numbers of optical interfaces, resulting in a increased throughput and return losses. Hybrid integration could improve this situation considerably and silicon substrate-based technology could play a significant role in this area.

1 Introduction

To support the emerging need for extremely high-speed interconnections in equipment backplanes (supercomputer interconnects), metropolitan area networks (MANs), and broadband local area networks (LAN), optical network technology with a high degree of concurrence may be necessary. In such environments, resources (transmitters, receivers, switches, and channels) need to be shared among multiple users. The main problem in an optical resource sharing system is controlling the access to the shared transmission, reception, or routing/switching resources. Without an efficient control, the bursty nature of data traffic in these networks can lead to severe "resource contention" even when the total utilization of each resource is well below its capacity. One way to deal with this issue is to deploy WDM technology in optical network architectures and use the added wavelength dimension to provide packet routing, switching or other functions in a collision free manner. The section below describes the details of the technique demonstrated in this project.

1.1 The concept of all-optical contention resolution

The information arriving on a single fiber at a node of a WDM-enhanced high speed network contains multiple channels carrying merged streams of packets statistically distributed in time. This gives rise to an occasional time-slot overlap among packets arriving on different data streams of the node receiver and subsequent loss of contending packets. Use of just a WDM device at the receiving node would require duplication of the node equipment, leading to increased cost and equipment complexity, since the packet sorting operation would have to be performed electronically at the speed of packet arrival at a further stage of the communication node. The use of delay lines to shift contending packets by one or more time slots can reduce, or virtually eliminate, the packet overlap (i.e. contentions). This original idea has been developed and evaluated at the University of Massachusetts. In order to perform this operation on a packet-by-packet basis, fast optical 2x2 switches must be used to allow rapid device reconfiguration. The net result of this switched delay line strategy, controlled by the local node intelligence, is the interleaving of packet streams into a single, contention free, channel of information with minimal loss of packets.

1.2 Principle of operation of the CRO

The switched delay line (SDL) CRO approach is applicable to different network systems and types of contention. The generic device is presented here as an isolated module, termed Contention Resolution Optic (CRO).

Figure 1 shows a diagram of a two-stage CRO. Two inputs contend for a single receiver, creating a throughput bottleneck. The state of the optical switches is set so that if two packets arrive at the two inputs at the same time slot, one is delayed in the optical delay line DL1 by one time slot. If a contention still exists, this operation is repeated in DL2. Calculations indicate that the network throughput increases significantly with the number of delay lines. For example, when applied to a two wavelength star system, CRO operation improves the channel efficiency from 0.75 (when no delay lines are used) to 0.92 and 0.95 with two and five delay line CRO, respectively.

The CRO device is based on the following two optical components: Delay Lines (DL-s) and 2x2 optical switches (S1,S2,S3). In particular, Figure 1 shows the CRO design which incorporates 2 DL-s and three 2x2 optical switches. Each DL delays a packet for one time slot and each 2x2 switch routes packets into and out of these DL-s.

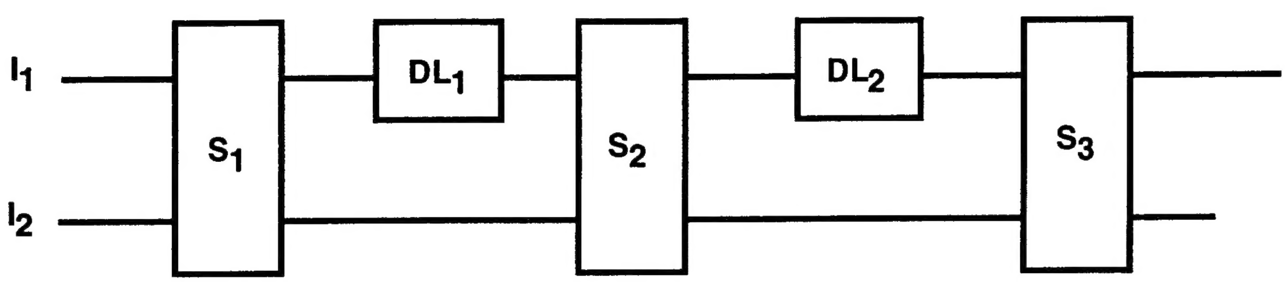

Figure 1: Schematics of the switched delay line two stage CRO.

On a time slot basis, each switch can be set up electronically either in the bar state or in the cross state. By optically propagating each packet through delay lines and optical switches comprising the CRO, O/E and E/O conversions of the packet payload and fast electronic buffering of in-transit information are avoided. Calculations indicate that the network capacity, throughput, average delay time, average number of transmissions per packet, packet loss probability, and better utilization metrics are all significantly improved by the use of the SDL-CRO. To demonstrate this principle, this project is using a star topology and a dual wavelength channel with two communication nodes.

1.3 Network demonstration

To demonstrate feasibility of this optical contention resolution approach, a star topology testbed has been constructed at Stanford University. The diagram of this demonstrator is shown in Figure 2 below. Each node operates at 2.5 Gbps and signals at two wavelengths (1.308 μm and 1.320 μm) contend for the receiver time through mixing in the network hub. The information is packetized in standard ATM packets. The CRO is a two-stage device (two delay lines) and thus includes three optical switches. To compensate for propagation and device coupling losses in the CRO module, three optical amplifiers have been added to this subsystem. In addition, header detection and polarization controls have been included for proper operation of the $LiNbO_3$-switch-unit where polarization sensitivity of the switches requires added controls.

The CRO performs optical packet serialization, resolving contentions in the optical domain. Three key component issues were addressed in this configuration. These include device losses, backreflections and polarization control.

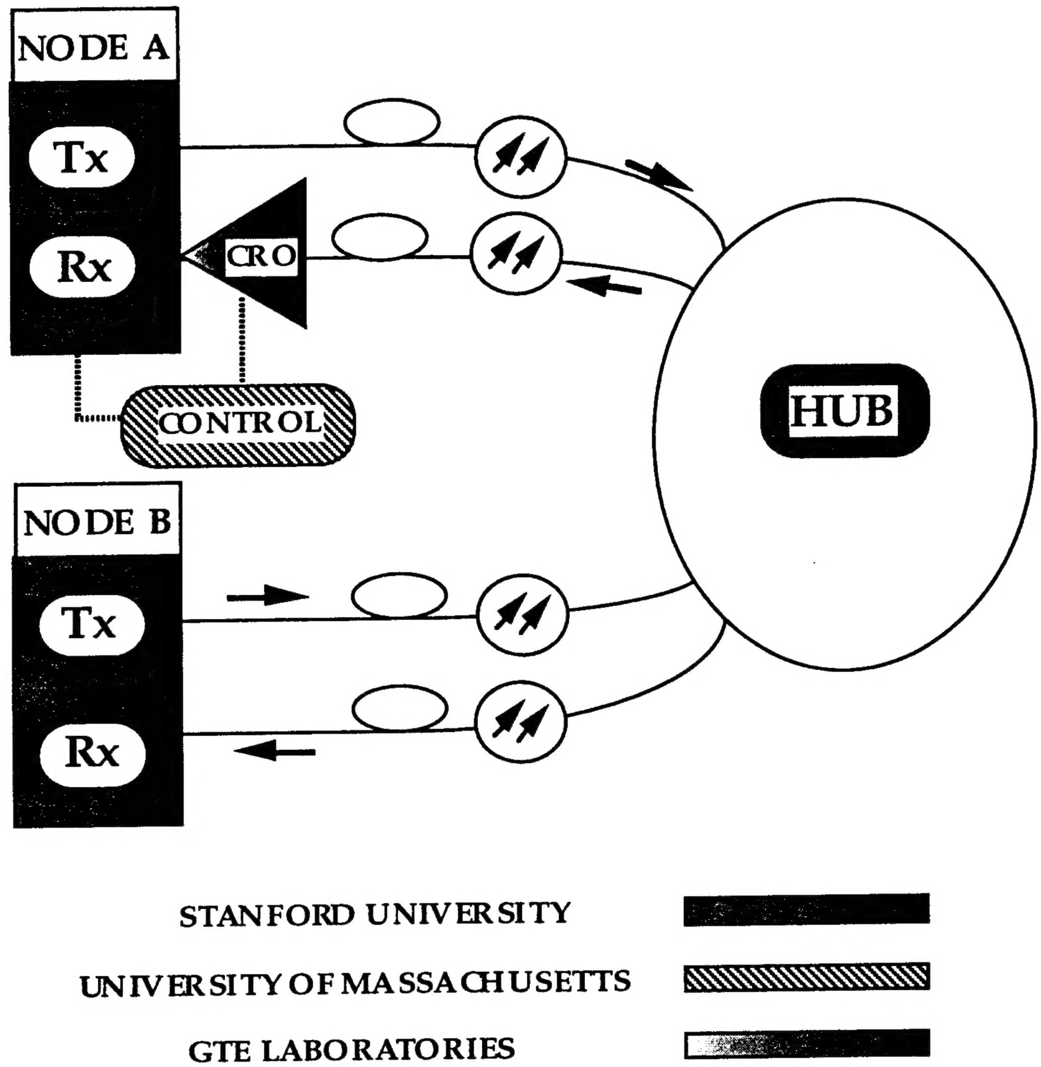

Figure 2. Network testbed configuration for feasibility demonstration of optical contention resolution.

2. Preprototype integration

The first phase in CRO construction involved building a single polarization device based on commercially available $LiNbO_3$ switches to provide as early as possible the key components for testing and fine-tuning the network demonstration. Work on this preprototype has included identification of components and vendors, specification of required characteristics and methodology for testing of the assembled module. A sketch of the CRO module is shown in Figure 3 with vendors identified wherever applicable. Splicing techniques for polarization maintaining fibers has been developed in this project using precision silicon v-groove technology.

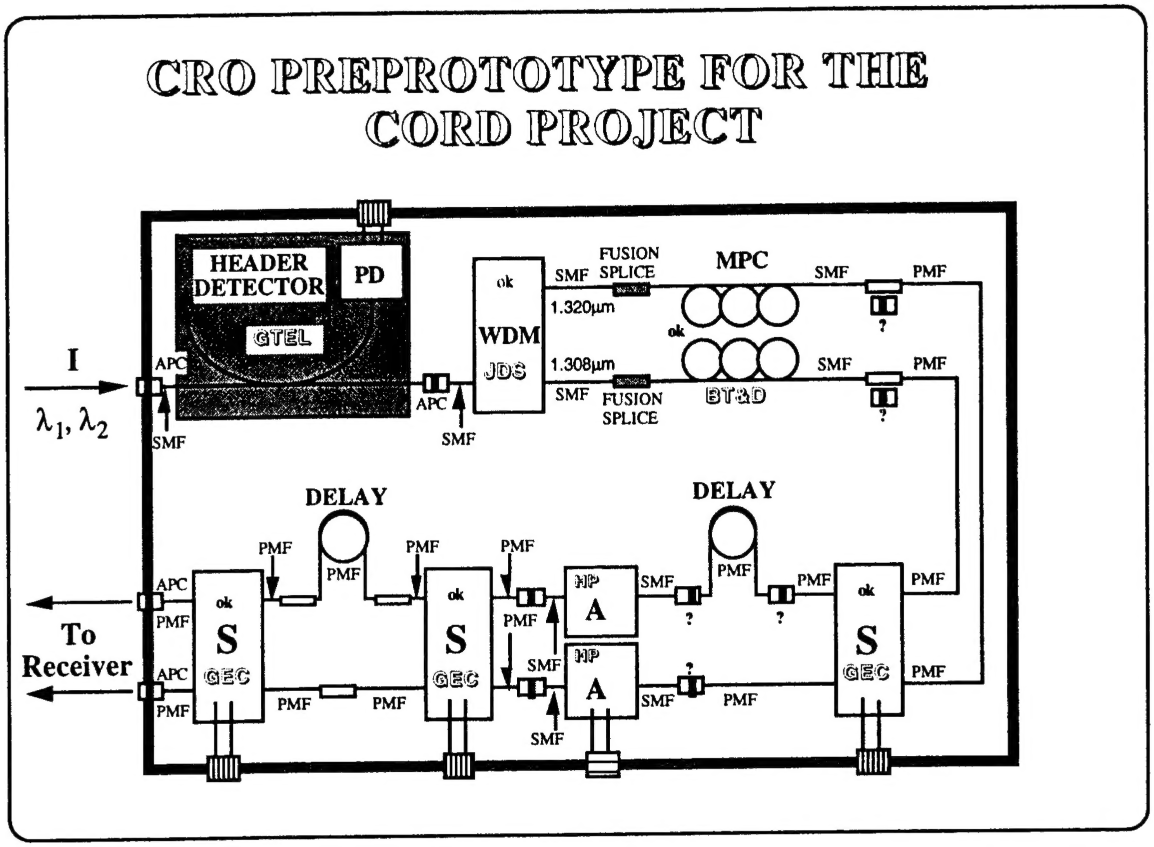

Figure 3. The CRO layout, topology and components.

The optical switches were purchased from GEC Marconi, which was the only vendor at the time supplying 2x2 fast switches. The units acquired were $LiNbO_3$ Mach-Zenders with response time of about 1 nsec, switching voltage of few volts (the exact value varied from one unit to another), and extinction ratio of about 20 dB. To achieve this performance the switches were made to operate on a single polarization state of the incoming optical signal. This feature makes it unsuitable for use in real systems (the polarization state of light propagating in optical fibers varies in time), but usable in a controlled laboratory environment. The insertion loss of these switching devices is about 5 dB per device.

The network demonstration was designed to switch standard ATM packets with 53 bytes (424 bits) which, at the rate of 2.5 Gbps, translates to 170 nsec per packet. Adding a time guard of 80 nsec for switching and synchronization inaccuracy defines a 250 nsec network time slot. This requires 50 meter delay lines in the CRO. The delay lines were made using polarization maintaining fibers--required due to the single polarization operation of the optical switches. The semiconductor optical amplifiers (SOA) were purchased from

Hewlett-Packard and all three units exhibited polarization imbalance of less than 2 dB and a gain of about 11-14 dB.

The preprototype components were extensively characterized with respect to their parameters relevant for this application.

2.1 WDM devices

Two Wavelength Division Demultiplexing devices made by JDS-Fitel are deployed in the CRO and were characterized before assembly. These devices were designed to operate at the wavelengths of 1308/1320 nm. The spectral response was measured by using a 1.3 µm LED as a broad-spectrum light source. Figures 4 and 5 show the spectral response of these two devices designated as WD1313U-AZM1308 and WD1313UA18M1308. The characteristics of both WDMs are almost identical. The results indicate that this type of demultiplexer provides sufficient isolation in the wavelength ranges of 1306 to 1314 nm for one channel with second channel centered at 1290 to 1300 nm or 1320 to 1330 nm.

A 1308 nm DFB laser diode was used to measure the insertion losses and the extinction ratios of these WDMs at 1308 nm. The results for both units are almost identical. The insertion in both channels is under 1.0 dB. The extinction ratio between the 1308 nm channel and 1320 is over 21 dB. These insertion loss and extinction ratio figures are polarization independent.

The back reflections of these WDMs were measured by using a Hewlett Packard 8504A Precision Reflectometer. These WDM devices exhibit very low levels of back reflections. Figures 4 and 5 show results of these measurements.

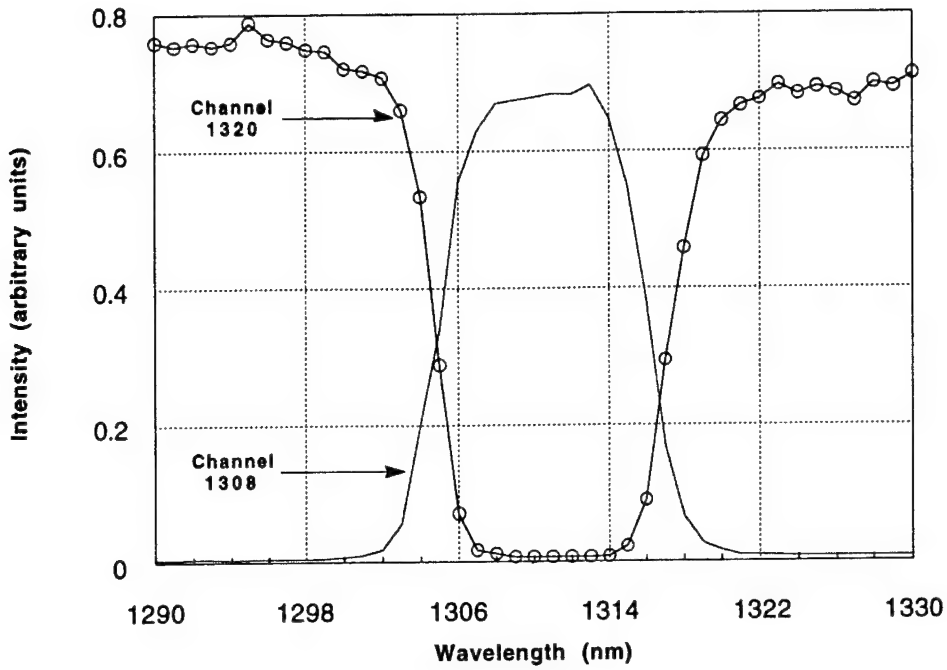

Figure 4. Spectral response of WDM unit WD1313U-AZM1308.

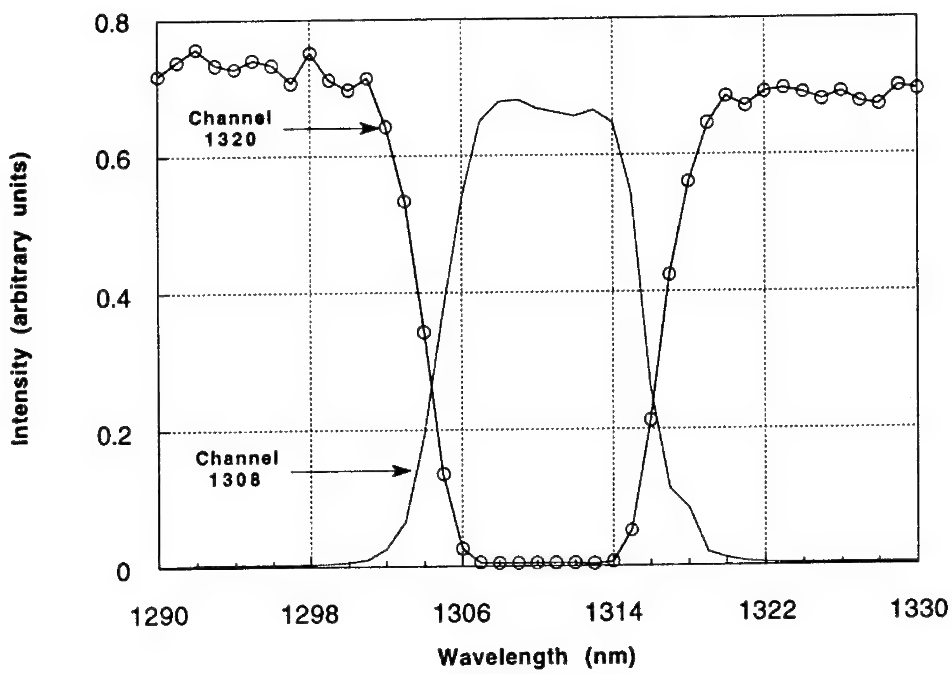

Figure 5. Spectral response of WDM unit WD1313UA18M1308.

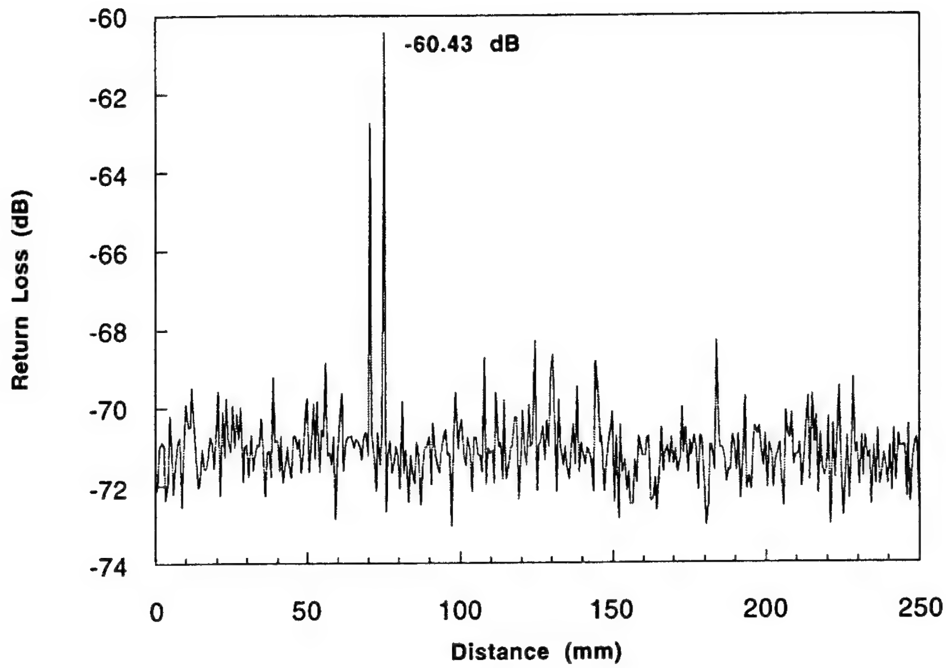

Figure 6. Back reflections in unit WD1313UA18M1308.

2.2 Preprototype Summary

The CRO preprototype module was built using commercially available components. The table below shows measured values of parameters related to optical losses and reflections in the various CRO components.

CRO LOSS TABLE

COMPONENTS	*No.* of Devices CH1	CH2	Insertion Loss per Device (dB)	Insertion Loss per Channel 1 (dB)	Insertion Loss per Channel 2 (dB)	Return Loss (dB)	Notes	Sources
Header Detector	1	1	-2.5	-2.5	-2.5	-55	10 % Tap .8A/W	GTE Labs
WDM	1	1	-1.5	-1.5	-1.5	-60	1308/1320 nm	JDS Fitel
MPC	1	1	0	0	0	No Reflection	All fiber	BT&D Tech
Polarization Monito	1	1	- 2	- 2	- 2	-55	5 % Tap Ratio	GTE Labs
FC/APC Connector	4	4	-0.5	- 2	- 2	-60	SM Fiber	JDS Fitel
PMF FC/APC Conn.	5	3	- 1	- 5	- 3	-60	Fujikura Panda	JDS Fitel
2X2 LiNbO Switch	3	3	- 5	-15	-15	-60	Fujikura Panda	GEC
Fusion Splice	7	6	-0.02	-0.14	-0.12	<-60	Single Mode Fiber	GTE Labs
V-Groove Splice	12	8	-0.2	-2.4	-1.6	<-60	SMF>PMF> PMF	GTE Labs
Delay	3	1	0	0	0	No Reflection	SMF or PMF	CORNING
Amplifier (GAIN)	2	1	14	28	14	1300 nm SMF In & Out		HP
TOTAL LOSS/CHANNEL				**-30.54**	**-27.72**	**dB**		
TOTAL GAIN/CHANNEL				**28.00**	**14.00**	**dB**		

The total net loss, compensated by SOAs in the main output channel (CH 1) is about 2.5 dB. This figure provides sufficient power margin for low BER operation of the node receiver. Further modifications at Stanford reduced the power loss by an additional 5 dB so that the final CRO module is almost lossless. The optical reflections, although low in magnitude must be watched carefully during system evaluation due to the large number of optical interfaces involved. This includes all of the fiber coupled components, as well as connectors and splices. Polarization control, even in a laboratory environment, presents a real issue. The unit was assembled at GTE Laboratories and made stable for a reasonably long period of time (hours). After shipment to Stanford University, this time was too short for operation and some of the polarization maintaining fibers had to be replaced by single polarization fibers for stable operation. To make fiber optic signal processing components usable in real systems all components must be polarization independent. Moreover, the issue of components packaging is critical in achieving practicality, both in cost and performance. For instance, the large number of interfaces would have to be reduced to keep losses and reflections at acceptable levels. Because of the complexity of monolithic integration, hybrid integration is one way to achieve these goals. Silicon waferboard precision silicon v-groove based technology for automation of fiber alignment are some of the advanced techniques that could be applied in that direction.

3 Digital Optical Switch

3.1 Four-electrode 2x2 switch

The first step toward the development of the semiconductor digital optical switch (DOS) was to fabricate and test 1x2 switch structures. This was successfully completed with an extinction ratio of >20 dB between the output switching arms by the beginning of this ARPA project. The next step, fabrication and testing of 2x2 switch structures, began in August of '93 with the design of a 4-electrode X-switch mask set. The completed mask set was received in October '93 from the mask vendor. A few initial fabrication runs were made with this new mask set on GTE's VPE-grown material. In November '93, MOCVD-grown wafers were ordered from EPI in England for use in this effort. The primary goal was to determine the appropriate active layer and cladding layer thicknesses and waveguide ridge width to assure consistent single-mode waveguides in the active region of the switch.

3.2 Waveguide Issues in DOS

While excellent results were achieved with 1x2 switches, as shown by record extinction ratios, progress was much slower for 2x2 switches during the first quarter of 1994. The primary problem was the presence of higher-order vertical-transverse spatial modes. Although the fundamental mode usually switched, the higher-order mode did not. This was consistent with our modeling, which showed that the vertical-transverse higher-order mode has a much larger step-index. The fraction of light initially injected into the unswitchable higher-order mode thus severely limited the 2x2 switches extinction ratio.

A 3-pronged 9-month-long effort was launched to find a solution to this problem. First, during the second quarter of 1994, a large number of weak-guiding switchable test-waveguides were fabricated and characterized to determine the effect of varying dimensions and processing procedures. It was found that the modal characteristics were not affected by fabrication processes (such as the addition of nitride or metalization), and therefore presumably the problems were not a result of fabrication-induced stress. However, the modal characteristics depended slightly on waveguide length. Longer chips were less prone to higher order modes, as consistent with higher propagation losses for the higher order mode. This observation was the basis for the next part of our effort to increase the device extinction ratio.

Second, we would take advantage of the demonstrated difference in loss between the fundamental and higher-order modes to "strip" the higher-order mode out of the waveguides. To this end, during the third quarter of 1994 a new test-structure mask was designed which incorporated long (5 cm) straight and curved waveguides of varying dimensions. Multiple devices were fabricated. These longer test structures permitted an accurate measurement of the differential loss, as well as the selective loss of the higher-order modes in the curved waveguides. Accurate loss measurements were not possible in our previous switches, due to their short length (~2 mm), but measurements on these waveguides gave losses on the order of 1 dB/cm for the fundamental mode and 30 dB/cm for the higher-order mode. This information was used in our final design to produce a switch which stripped out the higher-order modes and, therefore, operated in a single spatial mode with high extinction ratio.

Finally, as the third part of our 1994 effort, in parallel to the experimental effort, a more rigorous model was used to refine the switch design and identify a parameter space where

the switches are less sensitive to variations in growth and fabrication parameters (such as layer thickness and composition and ridge width). The limitations of the previous model, which used a one-dimensional effective-index approximation, had been reached, as verified by measurements of the near field beam profile. These measurements showed a triangular symmetry, which cannot be explained by a one-dimensional model. For this purpose, we contracted with the University of Waterloo to perform an exact, two-dimensional modeling analysis (using internal GTE funding) of a number of our waveguide structures over a 9 month period. The modeling results suggested that increasing the thickness of the InGaAs cap layer, and reducing the height of the ridge, would increase the loss of the higher order mode without affecting the loss of the fundamental mode. On the basis of these results, we ordered new wafers from EPI Products with this structure, and fabricated and characterized passive test-structures during the 4th quarter of 1994 to determine exact parameter values and confirm these results. This information was then used in our final switch design.

Three other minor problems developed in 1994, which were solved, but resulted in delaying our effort. First, a problem occurred during the deposition of the electrodes that resulted in shorting of the p-n junction, so that the switches were inoperable. The shorting cause was identified and remedied by adjusting the polyimide thickness and etching times to ensure that polyimide covered the sides of the ridges during metalization. Second, the increasingly lengthening delivery time of wafers from EPI slowed our progress. It was taking 3 months or more to receive an order from them. Sumitomo was added as a source of wafers to speed up the switch development process. Third, the building in which our characterization laboratory was housed underwent a year-long renovation. We were able to move the laboratory to a new location, but still incurred a two-month delay before characterization could resume.

3.3 2x2 X-switch design

The new mask set for the 2x2 X-switches, designed early in the first quarter of 1995, utilized curved waveguides to achieve a separation of 150 μm between the waveguide arm ends in the smallest amount of space. This permitted packaging of the switch with two input and two output fibers. The fibers approach the switch at an angle of about 22 degrees from the facet normal due to the refraction of the light, whereas the waveguides terminate at an angle of 7 degrees. The purpose of the 7 degree angle is the minimization of internal reflections, a critical requirement for broadband optical components.

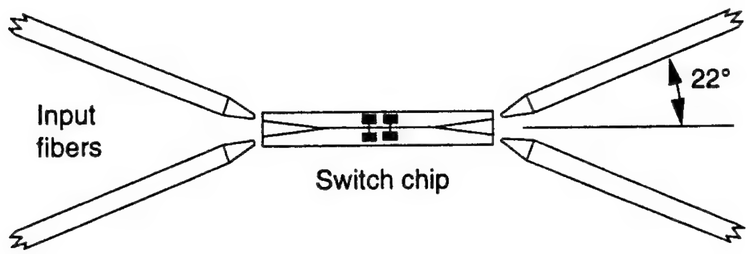

Figure 7. The 2x2 optical switch has on-chip input and output waveguides angled at 7° to the facet to minimize reflections. Refraction produces entrance and exit angles of about 22°.

Since the digital optical switch is a modal evolution device, where the index of refraction change caused by current injection modifies the propagation characteristics of the output mode and switches its intensity from one port to another, it is essential for its operation that the waveguides are single mode. Thus, the waveguides in this design were lower in ridge height (~1 μm) and narrower in width (3.5 μm), since the differential loss between the fundamental mode and the higher-order vertical-transverse modes is greatest in this structure. In addition, longer (~ 1 cm) input waveguide sections of the switch were used to act as higher-order mode-strippers to compensate for a less then perfect input coupling, which might excite a higher-order mode.

The complete 6-layer mask layout for the switch was completed early in February 1995 and a second set of plates was received from the vendor by the end of February. We suffered a two week delay when the first set of mask plates were delivered in unusable condition due to a bug in the vendor's software that fractured the design data and transmitted it to the mask maker.

Once mask plates for the new switches had been received from the vendor, fabrication and characterization of passive switch structures (modulators, X and Y-switches) were carried out to test the effectiveness of the new design in eliminating the higher order modes. Experimental results at the end of the first quarter of 1995 showed that the new design completely eliminated the higher-order modes in the waveguides. This was observed directly by examining the output beam profiles and through the use of single-wavelength

envelope modulation. The extinction ratio measured for the Y-switches was in the range of 15-25 dB. Figure 8 shows the power output of a Y-switch Vs applied current.

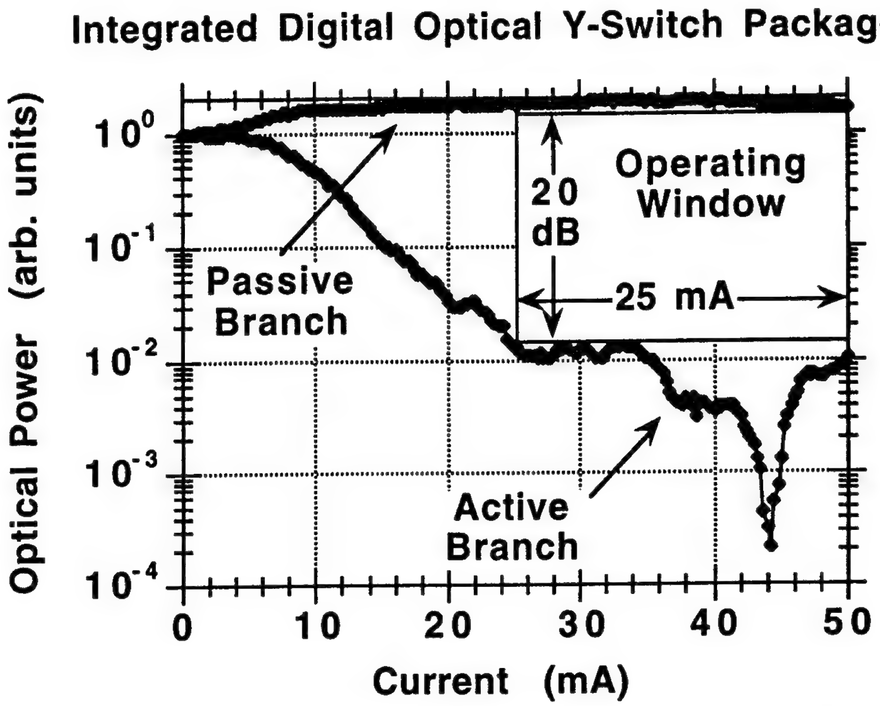

Figure 8. Optical output power of a Y-branching switch vs. applied current showing the wide range of control current (50% of Maximum) which gives an extinction ratio of over 20 dB.

The digital optical switch operates over a wide range of current values in the current injection mode. This is in contrast to interferometric switches (Mach-Zender or directional couplers), where the response is periodic in the applied control signal strength, and results in a very narrow range of control signal values for device operation in a high extinction ratio regime. For example, the $LiNbO_3$ switches used in the preprototype CRO (Mach-Zender) require regulation of the bias and switching voltages to within 1% to maintain the rated extinction ratio of 20 dB. More over, the digital optical switches do not require bias currents, simplifying the operation and making these devices much more practical. Figure 9 shows the range of switching currents used in testing the fabricated devices. For a range of about 10 mA about the nominal 30 mA, a good extinction ratio can be expected.

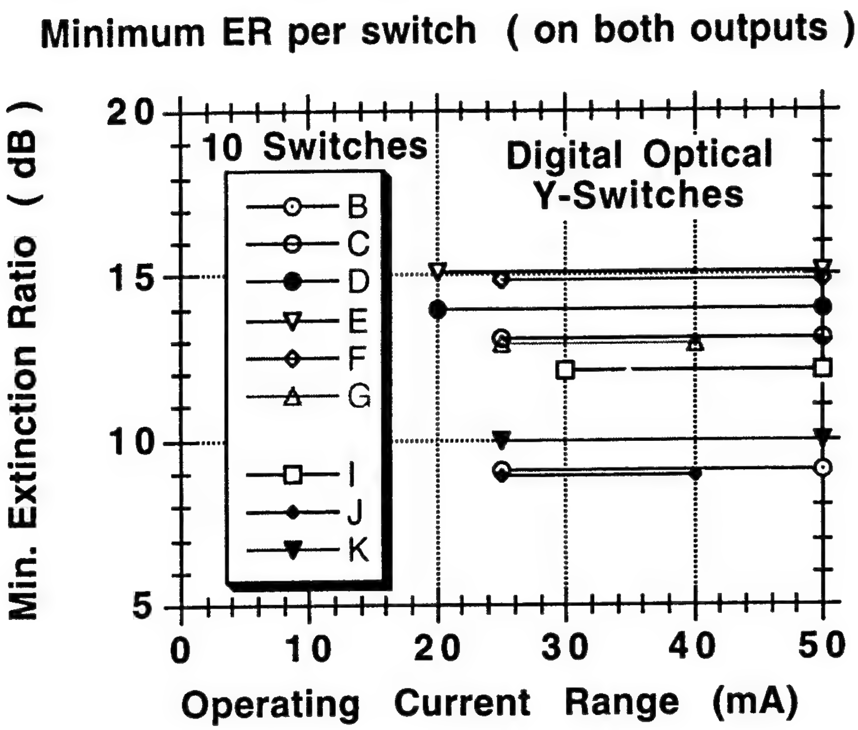

Figure 9. Minimum extinction ratio achieved from both output arms of the 10 best switches on one bar of 30 1/2° Y-branching switches vs range of applied current which achieves that minimum extinction ratio.

Also, during the first quarter of 1995, we learned that the devastating earthquake in Kobe interrupted our product's run and thus our alternative material supplier, Sumitomo, was now unable to supply us with any wafers for an unknown length of time, as their plant was highly damaged. A duplicate order was then placed with EPI products, our original supplier, who had not been able to ship on schedule.

3.4 Losses in DOS

An effort to eliminate waveguide-segmentation induced excess radiation loss of the curved waveguides in the packageable 2x2 X-switch occupied the second quarter of 1995. Measurements of the throughput losses on these devices revealed that the excess radiation losses in the curved sections of the packageable X and Y-switch structures were high (~12 dB/curve). This was traced to a feature of the design-software utilized in creating curves, it segmented curved sections. These segments were then re-connected by the mask generating program into a single curve. However, because of the way the software

performed this operation, jogs were formed in the fabricated waveguides causing optical power loss in the propagating signal. To reduce this loss, another RIE mask utilizing a larger number of segments (70) in each curved region was designed. This finer segmentation reduced the discontinuity in the waveguides and thus the losses. Devices fabricated with this mask showed a significant reduction in excess radiation losses by a factor of two (~5.6 dB/curve) in the curved regions. A third RIE mask, consisting of 600 segments and utilizing 0.05 μm resolution , was then designed to further reduce the radiation loss and devices were fabricated and characterized.

This third modification, increasing the number of segments in each curve to 600, did not produce the expected and required loss reduction in the curved input and output waveguides. Thus, our activity shifted from fabricating complete switches utilizing the existing mask set to solving this loss problem. Two solutions emerged, one focused on the curved waveguides radius of curvature, and the other on the degree of the optical mode's binding to the waveguide. Previously, all the curved waveguides fabricated had a bend of 7 degrees and a radius of curvature of 2 mm. Thus a new test mask with the existing 7 degree waveguide bend, but with 6 different larger radii of curvature (1, 2, 4, 8, 16, 32 mm) was designed and ordered. Using this mask, test wafers were fabricated and loss characterization of the curved waveguides was performed. These measurements provided a quantitative measure of the change in curved waveguide loss as a function of the change in radius of curvature of our weakly bound switchable waveguides. For example: (1) waveguides with a radius of curvature of 8 mm had a measured loss of ~ 5 dB/curve; (2) waveguides with a radius of curvature of 16 mm had a measured loss of ~ 3 dB/curve; (3) and with a radius of curvature of 32 mm had a loss of ~ 2 dB/curve. From an extrapolation of these results, it was estimated that curved waveguides with a 50 mm radius of curvature would incur a loss of ~ 1.5 dB/curve. This permitted the selection of a waveguide radius for a low-loss packageable switch mask design.

In addition, a second solution to the loss problem was devised. New processing procedures and masks were developed to etch additional material away from the cladding layer, in a limited region on each side of the curved input and output waveguides, to increase the binding of the optical mode to the waveguide and further reduce the loss. This technique experimentally proved out and gave us two different effective ways to produce low-loss curved waveguides for the switch. But the search for these solutions delayed us yet another 3 months to the end of the second quarter of 1995.

Also this quarter, a new characterization set up with adjustable fiber alignment at either of the two input ports (for X-switches only) at an angle of ~ 22^o from the perpendicular (separated from each other by ~44^o) and at either of the two output ports at similar angles (both X and Y-switches) was designed and built. This system is capable of simultaneously aligning fibers to packageable X-switches, two at the input and two at the output end for switch performance measurements. It was successfully used in characterizing the fabricated passive X-switch structures discussed in the next section.

3.5 The final packageable 2x2 X-switch design

Early in the third quarter of 1995, the previous 2x2 X-switch design was modified to have a 50 mm radius of curvature for the curved waveguides, utilizing 600 segments with 0.05 μm resolution. Since the overall geometry of the packagable switch changed, with the change in the radius of curvature of the curved input and output waveguides, two months of fabrication time were lost while a completely new packageable 6-level mask set was designed and ordered. It consisted of the RIE, nitride, scribe alley, guide, metal, polyimide and blocking masks.

To utilize the lost processing time profitably, a packageable switch wafer was fabricated utilizing the existing (2 mm radius of curvature) mask set with either the electrodes or polyimide or both omitted from selected switches on the wafer. Characterization of the straight waveguides, Y- and X-switches on this wafer, showed essentially the same loss as the previously measured complete switches. This confirmed that the high loss in the switches was due to the small radius of curvature of the waveguides, and not induced by an unknown mechanism in the further processing steps.

Also, the high-loss (2 mm radius of curvature) curved waveguide sections were cleaved off of the previously fabricated complete (with metal electrodes) earlier design packageable switches to permit characterization of the X-switch performance. The extinction ratios were found to be limited to ~ 10 dB due to two factors: (1) reflections from the small angle cleaves (1/4 degree) and (2) transverse current spreading in the older material wafer used in this fabrication. The first factor confirmed the value of incorporating low-loss curved waveguides at the input and output ends of a non anti-reflection coated X-switch to kill reflections from the chip interfaces as well as facilitate packaging of the device. The second

factor confirmed the value of having a reliable material supplier who could supply wafers on schedule.

In addition, the "proof of principle" of operation of 2x2 X-switches was demonstrated using X-switches fabricated with the initial non-packageable switch mask set. Since that mask design was not optimized for single mode operation, the waveguides supported higher-order modes. This made the output characteristics of both the active and the passive arms oscillatory. Thus, acceptable extinction ratios (~10 dB) could only be obtained at those values of injection currents where the higher-order modes have a minimum, which was different for each electrode and switch. The extinction ratio also changed with the alignment of the fibers, because the mixture of the higher-order modes changes with fiber alignment. Thus, acceptable performance was not attainable. Since the use of the newly designed packageable mask set eliminates the higher-order modes from the waveguides completely, it is expected that the switches fabricated using this mask set will demonstrate much better performance in terms of extinction ratios.

Once the new final switch masks were on hand, passive switch test-structures were fabricated on the recently received EPI wafers Preliminary loss characterization of the devices clearly showed that the excess loss of the curved input and output waveguides (at 50 mm radius) was at or below our ability to measure. In addition, another passive switch wafer, similar to the one just mentioned, except that the curved regions utilized tighter binding waveguides, was characterized and showed no measurable excess loss due to the curved input and output waveguides. This activity brought us to the end of the third quarter of 1995.

The first complete (with switching electrodes) packageable 2x2 X-switches were fabricated during the fourth quarter of 1995. Unfortunately, the first two wafers suffered processing defects. One was over-etched, producing too narrow ridge waveguides with a high fundamental-mode loss, and the other was broken during final cleaving. Additional wafers are being processed and will be ready for characterization by the end of the fourth quarter of 1995. This effort will continue during the first half of 1996 under internal GTE funding.

In addition, for X-switch demonstration purposes early in 1996, a new portable set-up consisting of four micro-positioning control stages, two for the input fibers and two for the output fibers, was assembled. The switch electrodes are connected to external current

sources via bonding pads attached to the sample holder for compactness, rather then using probe needles, as has been done previously. The whole mechanical set-up is mounted on a small hand-portable optical bench, and will allow easy transport of the switch to various system labs for preliminary testing, before a completely packaged device is available.

3.6 Summary.

The Digital Optical Switch development effort has made considerable progress over the contract period, but stopped short of producing a packaged device needed for system demonstration. The two year duration turned out to be sufficiently long to resolve many technical feasibility demonstration issues and to develop practical designs, however development of packageable devices required substantial additional efforts. Delays in delivery of parts, in particular semiconductor wafers, slowed down much of the early development momentum and added many months to the component development cycle. Therefore, most of the achievements and progress were made in feasibility demonstration rather than prototype production. These include fabrication and operation of 1x2 digital optical switch. The fabricated devices switch at relatively low current values (~ 15 mA) opening the option for multi-element assemblies. Also, this version of the switch shows a very high extinction ratio (ER > 20 dB) over a wide range of control currents (~ 50 %). This is in contrast with interferometric devices (e.g. LiNbO3 based Mach-Zender) where 1% is the more typical figure. In contrast with interferometric devices, there is a large tolerance to switching current values. For most of the tested device this was about 50% of the switching current, contributing to the practicality of this device.

This switch development program addressed one of the basic issues in semiconductor based waveguide components. This is the issue of multi-mode operation of passive devices even when the waveguides are single mode. This is due to the short propagation distances and the high index of the substrate. For the DOS this is a key for good performance. In this project the higher-order transverse "Leaky Modes" were eliminated from both the 1x2 and 2x2 weakly guiding switch structures by implementing a more advanced two-dimensional exact waveguide modeling analysis and incorporating its predictions to the switch waveguide design.

Development of the 2x2 digital optical switches has progressed to the stage of "proof of principle" operation. Initial devices were fabricated and the switching action observed. The

extinction ratio measured was about 10 dB. This difference between 1x2 and 2x2 devices is most likely due to the need for different waveguide cross angle in the two cases. This optimization process has not been yet completed.

In order to package the optical switch, the input and output waveguides must be sufficiently separated to allow attachment of two fibers. This requires at least 250 μm separation. To achieve that, low-loss curves must be incorporated into the waveguide geometry. This was completed and 50 mm curves were designed, fabricated and showed low loss at 1.3 μm. Devices made with curving input/output waveguides were characterized and exhibit excellent extinction ratio of 20 dB.

As a general comment about this effort, to make fiber optic signal processing components useable in real systems all in-line components (fiber in/fiber out) must be polarization independent. Moreover, the issue of component packaging is critical in achieving practicality both in cost and performance. For instance, the large number of interfaces in the CRO module must be reduced to keep losses and reflections at acceptable levels. Because of the complexity of monolithic integration, hybrid integration is one way to achieve these goals. Silicon waferboard and precision silicon v-groove based technology for automation of fiber alignment are some of the advanced techniques that could be applied in that direction.